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## THE SEARCH FOR OTHER EARTHS: LIMITS ON THE GIANT PLANET ORBITS THAT ALLOW HABITABLE TERRESTRIAL PLANETS TO FORM

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## ABSTRACT

Gas giant planets are far easier than terrestrial planets to detect around other stars, and are thought to form much more quickly than terrestrial planets. Thus, in systems with giant planets, the late stages of terrestrial planet formation are strongly affected by the giant planets' dynamical presence. Observations of giant planet orbits may therefore constrain the systems that can harbor potentially habitable, Earth-like planets. We present results of 460 N-body simulations of terrestrial accretion from a disk of Moon- to Mars-sized planetary embryos. We systematically vary the orbital semimajor axis of a Jupiter-mass giant planet between 1.6 and 6 AU, and eccentricity between 0 and 0.4. We find that for Sun-like stars, giant planets inside roughly 2.5 AU inhibit the growth of 0.3 Earth-mass planets in the habitable zone. If planets accrete water from volatile-rich embryos past 2-2.5 AU, then water-rich habitable planets can only form in systems with giant planets beyond 3.5 AU. Giant planets with significant orbital eccentricities inhibit both accretion and water delivery. The majority of the current sample of extra-solar giant planets appears unlikely to form habitable planets.

*Subject headings:* planetary systems: formation — methods: n-body simulations — astrobiology

## 1. INTRODUCTION

In systems with gas giant planets, there exists an unavoidable link between terrestrial and giant planets. Giant planets are constrained to form during the few million year lifetime of the gaseous component of protoplanetary disks (Haisch *et al.* 2001). On the other hand, terrestrial planets take tens of millions of years to form in a bottom-up fashion from km-sized planetesimals through Moon- to Mars-sized planetary embryos (see review by Chambers 2004). Thus, giant planets are present during the late stages of terrestrial accretion. It is during this late stage that water may be accreted by terrestrial planets in the form of water-rich bodies originating past  $\sim 2.5$  AU (Morbidelli *et al.* 2000; Raymond, Quinn & Lunine 2004 – hereafter RQL04; see Drake & Righter 2002 for a different opinion). Indeed, the gravitational influence of the giant planets can shape the orbital and compositional characteristics of systems of terrestrial planets (e.g., Chambers & Cassen 2002; Levison & Agnor 2003; RQL04).

Estimates of the fraction of Sun-like stars with massive planets range from 5% to 25%, although these values depend on the semimajor axes of the planets in question (Tabachnick & Tremaine 2002, Lineweaver & Grether 2004, Fischer & Valenti 2005). This fraction appears to be significantly lower for low-mass stars (Endl *et al.* 2006). In addition, Greaves *et al.* (2006) saw no correlation between the presence of debris disks and giant planets, suggesting that many terrestrial planet systems may not contain giant planets. By studying the link between giant and terrestrial planets, we are restricting ourselves to the subset of planetary systems containing giant planets; note that this subset still comprises billions of stars in our Galaxy.

Previous work has documented correlations between the giant and terrestrial planets. Systems with more massive giant planets tend to form fewer, more massive terrestrial planets than systems with less massive giant planets (Levison & Agnor 2003; RQL04). In addition, giant planets with significant orbital eccentricities preferentially eject water-rich material in the outer disk and cause the terrestrial planets to be dry (Chambers & Cassen 2002; RQL04).

Several studies have used massless test particles to search for stable regions in the known extra-solar systems of giant planets (e.g., Jones *et al.* 2000; Rivera & Lissauer 2001; Menou & Tabachnik 2003; Barnes & Raymond 2004). These stable regions are considered locations where Earth-like planets might exist. However, this method is limited because forming planets do not behave as massless bodies – indeed, such studies would predict the existence of an Earth-sized planet at 3 AU in the asteroid belt. However, gravitational jostling among embryos in moderately stable regions like the asteroid belt (which is pervaded by resonances with the giant planets) removes the vast majority of the mass in the region (Wetherill 1992). For example, Barnes & Raymond (2004) found stable regions for test particles in four extrasolar planetary systems, but later work showed that terrestrial planets could only form in two of the systems (Raymond, Barnes & Kaib 2006). Only a few authors have studied the formation of terrestrial planets in known extra-solar systems (Th  bault *et al.* 2002, 2004; Quintana *et al.* 2002; Raymond, Barnes & Kaib 2006).

In this *Letter* we derive limits on the extra-solar giant planet systems that are likely to harbor potentially habitable planets. This is designed as a guideline for upcoming missions searching for extra-solar Earths, such as ESA's *Darwin* and NASA's *Kepler* and *Terrestrial Planet Finders*. Specifically, our goal is to determine the region in the orbital parameter space of a giant planet where potentially habitable planets can form in the habitable zone.

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With a sample size of one, it is difficult to decide which theoretical planets could harbor life. For this analysis, we require potentially habitable planets to 1) form in the circumstellar habitable zone (Kasting *et al.* 1993), 2) have a minimum mass of 0.3 Earth masses ( $M_{\oplus}$ ) – below this value planets are unlikely to sustain plate tectonics for many Gyr (Williams *et al.* 1997; Raymond, Scalo & Meadows 2006), and 3) have a significant water content. Not only is water thought to be vital for life, it may also help with plate tectonics (Regenauer-Lieb *et al.* 2001).

We simulate the formation of terrestrial planets from a disk of planetary embryos in the presence of a single, Jupiter-mass giant planet. We systematically vary the giant planet’s orbital semimajor axis between 1.6 and 6 AU, and its eccentricity between 0 and 0.4. Simulation outcomes constrain the systems in which terrestrial planets can form, and provide an observational test of which extra-solar systems are able to form habitable planets. We extend our analysis to stars of different masses and compare with the known sample of extra-solar giant planets.

## 2. SIMULATIONS

We start from a protoplanetary disk that extends from 0.5 to 4 AU with a surface density distribution that scales with radial distance  $r$  as  $\Sigma(r) = \Sigma_1 r^{-3/2}$ . We choose  $\Sigma_1$ , the surface density at 1 AU, to be  $10g\,cm^{-2}$ , about 50% higher than the minimum-mass solar nebula model (Hayashi 1981). We assume that planetary embryos have formed in the disk, spaced by  $\Delta = 5$ –10 mutual Hill radii, as predicted by models of oligarchic growth (e.g., Kokubo & Ida 1998). We generate four disks, each with 46–49 embryos. Embryo masses  $M$  increase as  $M \propto \Delta^{3/2} r^{3/4}$  (e.g., RQL04) and range from roughly 0.03 to 0.3  $M_{\oplus}$ , totalling 6.2  $M_{\oplus}$ .

Embryos start with a water distribution that reflects the current distribution of water in primitive classes of asteroids (Abe *et al.* 2000; see Fig. 2 from RQL04): inside 2 AU embryos are dry, outside 2.5 AU they are wet (5% water by mass) and from 2–2.5 AU they contain a moderate amount of water (0.1% water by mass; see first panel of Fig. 1). We also assign embryos a starting iron content that is interpolated between the known values for the planets (as in Raymond *et al.* 2005a, 2005b), including a dummy value of 40% iron by mass in place of Mercury because of its anomalously large iron content.

We assume that one Jupiter-mass giant planet exists in the system. We vary its semimajor axis  $a_J$  between 1.6 and 6.0 AU (spaced every 0.2 AU), and its eccentricity  $e_J$  between 0.0 and 0.4 (spaced every 0.1). These initial conditions inherently assume that embryos form more quickly than giant planets (as in the core-accretion scenario; e.g., Pollack *et al.* 1996). In cases with small  $a_J$  or large  $e_J$ , embryo formation may be unlikely in certain regions of the disk (due to strong resonances and high planetesimal velocities). However, those embryos whose formation is in question are quickly removed from the system via dynamical ejection. Thus, we consider our simulations a reasonable approximation of terrestrial accretion even if giant planets form more quickly than embryos (e.g., Boss 1997).

For each  $(a_J, e_J)$  combination we perform four simulations of terrestrial planet growth, i.e. one for each disk of embryos we’ve generated, for a total of 460 sim-

ulations. We integrate each simulation for 200 million years with a 6 day timestep using the hybrid integrator *Mercury* (Chambers 1999). Collisions are treated as inelastic mergers conserving water and iron (for a discussion, see Raymond, Quinn & Lunine 2006b). Each simulation conserved energy to better than one part in  $10^3$ .

Low-resolution simulations such as these can reproduce the bulk properties of the Solar System (Agnor *et al.* 1999, Chambers 2001). So, although a given simulation may lack certain details of a high-resolution simulation (Raymond, Quinn & Lunine 2006a), the large number of simulations we run should reproduce the basic properties of the planetary systems. Indeed, since computational speed scales with the number of particles  $N$  as  $N^2$ , low-resolution simulations are ideal for explorations of parameter space.

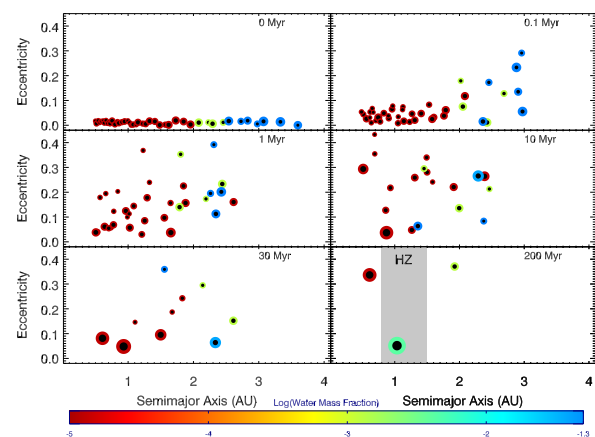


FIG. 1.— Snapshots in time of the evolution of a simulation with a zero eccentricity giant planet at 4.2 AU. The size of each body indicates its relative physical size, but is not to scale. The color represents its water content, and the dark circle in the center shows the size of its iron core. In this case a water-rich, 1.6  $M_{\oplus}$  planet formed at 1.03 AU in the HZ (shaded in the last panel).

Figure 1 shows the evolution of a simulation with  $(a_J, e_J) = (4.2\text{ AU}, 0.0)$ , color-coded by water content. The outer regions of the disk are excited by interactions with Jupiter (e.g., the 2:1 mean motion resonance at 2.6 AU), and the inner disk is excited by gravitational perturbations among embryos. As eccentricities increase, orbits cross and collisions occur. In time, planets grow and the number of bodies dwindles. Many embryos are scattered from their original locations, sometimes delivering water-rich material to planets in the inner regions. Water delivery occurs relatively late in the evolution, because multiple scattering events are needed for significant radial movement (Raymond, Quinn & Lunine 2006a). In this case three terrestrial planets formed, at 0.61, 1.03 and 1.94 AU. The planets at 1.03 and 1.94 AU accreted material from past 2.5 AU, but the inner planet is dry.

Figure 2 shows the regions in  $(a_J, e_J)$  space where potentially habitable terrestrial planets can form. Crosses mark regions where no terrestrial bodies survive in the habitable zone (HZ), defined to lie between 0.8 and 1.5 AU (see shaded region in ‘200 Myr’ panel from Fig. 1). Red dots indicate regions where terrestrial bodies survive in the HZ but average less than 0.3  $M_{\oplus}$ . Green dots mark where the average mass of terrestrial planets

in the HZ exceeds  $0.3 M_{\oplus}$ , but these planets have not accreted water-rich material from past 2-2.5 AU. Blue dots indicate where planets in the HZ have average masses greater than  $0.3 M_{\oplus}$  and average water contents greater than  $5 \times 10^{-4}$  by mass (a rough lower limit on the Earth’s water content).

Figure 2 shows clear limits to where habitable planets can form, despite some scatter due to the stochastic nature of the accretion process (e.g., the lack of  $0.3 M_{\oplus}$  planets for  $(a_J, e_J) = (5.2 \text{ AU}, 0.1)$  and  $(6.0 \text{ AU}, 0.0)$  and their presence at  $(1.8 \text{ AU}, 0.0)$ ). Habitable-mass ( $> 0.3 M_{\oplus}$ ) planets can form in the HZ if  $a_J > 2.5 \text{ AU}$ . Water-rich habitable-mass planets can only form for  $a_J > 3.5 \text{ AU}$ . The criterion that planets must accrete water-rich embryos (i.e., the blue dots) is “noisier” than our  $0.3 M_{\oplus}$  planetary mass criterion because the spacing between embryos increases with orbital distance, such that only  $\sim 10$  water-rich embryos exist at the start of each simulation. Small-number statistics is therefore responsible for the noise in the data. However, high-resolution simulations have demonstrated that the water delivery process is actually much more robust (less stochastic) than previously thought (Raymond, Quinn & Lunine 2006b).

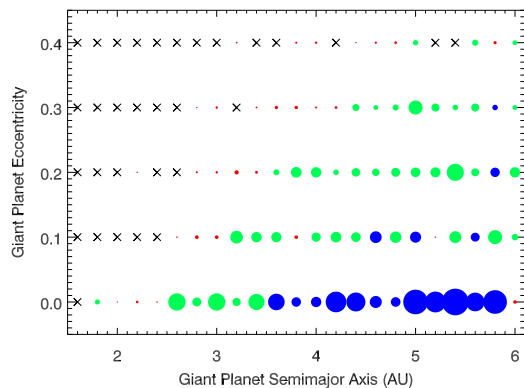


FIG. 2.— Regions in giant planet orbital parameter space that permit the formation of a habitable terrestrial planet. Crosses indicate where no terrestrial bodies survived in the HZ (defined as 0.8-1.5 AU). In systems with red dots, terrestrial bodies survived in the HZ but averaged less than  $0.3 M_{\oplus}$ . In systems with green dots, terrestrial planets in the HZ averaged more than  $0.3 M_{\oplus}$ . Systems with blue dots formed habitable planets in the HZ, with masses averaging over  $0.3 M_{\oplus}$  and water contents averaging more than  $5 \times 10^{-4}$  (roughly the Earth’s water content). The sizes of dots is proportional to the total surviving mass in the HZ.

These limits for Jupiter’s orbital distance apply only for a single giant planet system. Other, more distant giant planets would induce secular resonances (e.g., the  $\nu_6$  secular resonance in the asteroid belt) and make it more difficult for terrestrial planets to form. Thus, if multiple giant planets existed in a system, the limits derived above in Fig. 2 would be lower limits – most likely, the innermost giant planet would have to be farther from the central star for a habitable planet to form.

At higher eccentricities the critical values of  $a_J$  for habitable planet formation are higher. This is not surprising, as both secular and resonant perturbations increase with eccentricity. An eccentric giant planet ejects

a larger fraction of embryos, increases planetary eccentricities, and causes planets to form closer to the central star than for a zero-eccentricity giant planet (Levison & Agnor 2003). In addition, water-rich embryos past 2-2.5 AU are much more likely to be ejected by an eccentric giant planet, so the terrestrial planets’ water contents are decreased (Chambers & Cassen 2002; RQL04).

These results are for a fixed mass protoplanetary disk. However, observations suggest that there exist a range of disk masses (e.g., Andre & Montmerle 1994, Eisner & Carpenter 2003, Andrews & Williams 2005). In addition, the disk mass scales with stellar mass, with important implications for the amount of material available for terrestrial planet formation (Raymond, Scalo & Meadows 2006). The disk’s density profile also affects the location of planets that form (Raymond *et al.* 2005b).

### 3. APPLICATION TO KNOWN EXTRA-SOLAR SYSTEMS OF GIANT PLANETS

We adopt the two limits from Section 2: 1) habitable-mass ( $> 0.3 M_{\oplus}$ ) planets can only form in the HZ if  $a_J > 2.5 \text{ AU}$  and 2) water-rich habitable planets if  $a_J > 3.5 \text{ AU}$ . To extend this to different stellar masses, we assume that the ratio of orbital periods of these limits and the outer edge of the HZ is constant. The location of the HZ  $a_{HZ}$  scales with the stellar flux, i.e. with the stellar luminosity  $L_{\star}$  as  $L_{\star}^{0.5}$ . We assume that the boundary beyond which water-rich material can exist in the disk also scales with the stellar flux, and so do the  $a_J$  limits for  $> 0.3 M_{\oplus}$  and water-rich planets. For the mass-luminosity relation of low-mass stars, we use a fit to data of Hillenbrand & White (2004).

Figure 3 shows our derived limits on a giant planet’s orbital distance for  $> 0.3 M_{\oplus}$  planet formation (dashed line) and water-rich planet formation (solid line) as a function of stellar mass. Circles represent the known extra solar planetary systems detected via the radial velocity technique (with updated orbital fits and stellar data from Butler *et al.* 2006 and references therein; we only considered the outermost planet in multi-planet systems). Since this is a slice in a many-dimensional space, variables such as giant planet mass and eccentricity are not shown in Fig. 3. Filled circles indicate giant planets with low enough eccentricities to indeed form  $0.3 M_{\oplus}$  planets in the HZ, and filled triangles mark the two systems that can form water-rich planets (see below).

Only nine of the 153 planetary ( $\sim 6\%$ ) systems considered fit our criteria for being able to form habitable-mass planets. Two of these are multi-planet systems with an additional giant planet closer to the HZ, making it unlikely for terrestrial bodies to survive in the HZ. Thus, only seven of 153 (5%) known giant planet systems are likely to form potentially habitable planets. Two of these are able to form water-rich planets in the HZ: 55 Cnc (as shown by Raymond, Barnes & Kaib 2006) and HD 89307. The five other systems that can form  $0.3 M_{\oplus}$  planets in the HZ are Epsilon Eridani, HD 111232, HD 114386, HD 146922, and HD 70642. If their eccentricities are small, two planets recently discovered by microlensing surveys would also fit both of our  $a_J$  criteria: the  $5.5 M_{\oplus}$  planet OGLE-2005-BLG-390Lb (Beaulieu *et al.* 2006) and the  $\sim 13 M_{\oplus}$  planet OGLE-2005-BLG-169 (Gould *et al.* 2006).

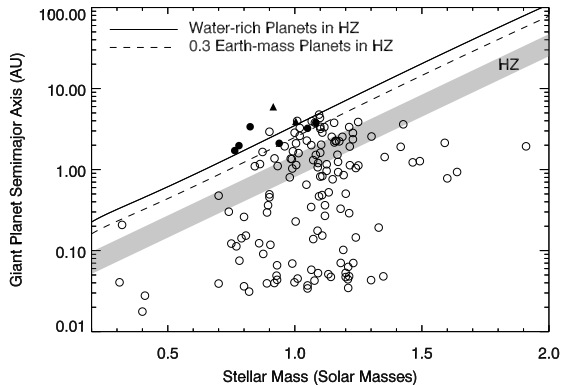


FIG. 3.— Limits in stellar mass-giant planet semimajor axis space where habitable planets can form. Above the dashed curve,  $0.3 M_{\oplus}$  planets can form in the HZ. Above the solid curve, water-rich  $0.3 M_{\oplus}$  planets can form in the HZ. The open circles indicate known giant planets. Filled circles indicate the giant planets which also have appropriate eccentricities for the formation of habitable-mass planets. Filled triangles indicate giant planets that can form water-rich  $0.3 M_{\oplus}$  planets in the HZ. The HZ is shaded.

#### 4. DISCUSSION AND CONCLUSIONS

In this *Letter* we have placed rough limits on where habitable terrestrial planets can form as a function of the orbital semimajor axis  $a_J$  and eccentricity  $e_J$  of a Jupiter-mass giant planet. These limits can be used as guidelines to direct the search for extra-solar Earth-like planets. We find that, for  $> 0.3 M_{\oplus}$  planets to form in the habitable zone (HZ),  $a_J$  must be larger than 2.5 AU. If planets accrete water from volatile-rich embryos past 2–2.5 AU, then water-rich,  $> 0.3 M_{\oplus}$  HZ planets can form if  $a_J > 3.5$  AU. If, however, embryos originating in the HZ are hydrated (Drake & Righter 2002), then our limit for water-laden planets is identical to our  $0.3 M_{\oplus}$  formation limit.

We have only considered Jupiter-mass giant planets. More massive planets are stronger perturbers and will have habitable planet limits at larger  $a_J$ . In addition, there might exist systematic links between planetary mass and stellar mass: 1) Jupiter-mass planets may be unlikely to form around low-mass stars (Laughlin *et al.* 2004), and 2) the surface density of material scales with the stellar mass, so less material is available for building planets around low-mass stars. Indeed, Earth-mass planets may be rare around low-mass stars (Raymond, Scalo & Meadows 2006).

We have not considered giant planet migration in these simulations. As a giant planet forms in the outer disk and migrates inward, moving resonances can “push” in

front of it a pile-up of material (Fogg & Nelson 2005; Mandell, Raymond & Sigurdsson 2006, in preparation). If the giant planet stopped migrating at 2 AU, an Earth-mass planet could potentially form just inside the 2:1 resonance, at 1.27 AU in this case. However, the stability of such a planet is unclear, as it would have migrated into a disk of planetary embryos. Self-scattering of embryos into resonances with Jupiter is thought to be the main cause of the depletion of the asteroid belt (Wetherill 1992). Although such a terrestrial planet might be more massive than the embryos, it would already lie close to strong resonances with the giant planet. The fate (and even the formation) of such a planet is uncertain.

Planetary systems with inner giant planets (e.g., “hot jupiters”) may support terrestrial planets in the HZ (Raymond *et al.* 2005a; Mandell *et al.* 2006, in preparation). In these systems, habitable planets would be built of rocky/icy material that survived giant planet migration through the terrestrial region. Raymond *et al.* (2005a) found that low-eccentricity giant planets inside about 0.5 AU are able to form habitable planets.

Most of the detected giant planets are at relatively small orbital distance and have significant orbital eccentricities. Only seven out of 153 planetary systems ( $\sim 5\%$ ) from Butler *et al.* (2006) meet our criterion for the formation of  $> 0.3 M_{\oplus}$  planets, and only two meet our limit for water-rich planets to form in the HZ. However, if we arbitrarily assume that habitable planets can form in systems with giant planets interior to 0.5 AU with eccentricities less than 0.1 (roughly following from Raymond *et al.* 2005a), then the number of known extra solar systems that could harbor habitable planets increases to 45 (29%).

Many planetary systems may not harbor giant planets but still allow terrestrial accretion to occur (Greaves *et al.* 2006; Raymond, Scalo & Meadows 2006). Thus, the abundance of potentially habitable terrestrial planets may not be tied to the abundance of giant planets. Extra solar Earths will be found and characterized by upcoming missions such as *Kepler*, *COROT*, *SIM*, *Darwin* and *Terrestrial Planet Finder*. We eagerly await these new discoveries.

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